4-gc Parametric Amplifier for Satellite Communication Ground Station Receiver

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This paper describes the design and performance of a 4-gc parametric amplifier which meets the stringent requirements of a satellite ground station receiver. It consists of two cascaded stages of similar design: the first of these is operated at liquid nitrogen temperature and the second at room temperature. One 23-gc pump source is used for both amplifier stages. The combination of the two amplifier stages provides 38-db over-all gain, 45°K over-all system input noise temperature, 60-mc bandwidth, 0.1-db short-term gain stability and 0.3-db long-term gain stability. A carefully designed cryogenic system maintains the amplifier refrigerated with only infrequent refilling of the dewar, i.e., once every 10 days.

I. INTRODUCTION

High sensitivity, stability and reliability are important requirements for a satellite communication ground station receiver. The maser has come to be considered the ideal preamplifier for satellite communication due to its superlative low-noise performance, and it is indeed ideal for cases where its cost and maintenance requirements are not of major concern. However, for lighter traffic routes where cheaper terminals are required, it is desirable to have a less expensive, more compact, and more easily maintained microwave preamplifier. This has motivated the development of the variable capacitance parametric amplifier described in this paper.

A block diagram of the parametric receiver is shown in Fig. 1. The receiver consists of four major sections: a circulator type parametric amplifier, an extremely stable 23-gc pump source, an efficient cryogenic system, and a control system. The first-stage amplifier is operated at liquid nitrogen temperature. The varactor diode mount, circulator,

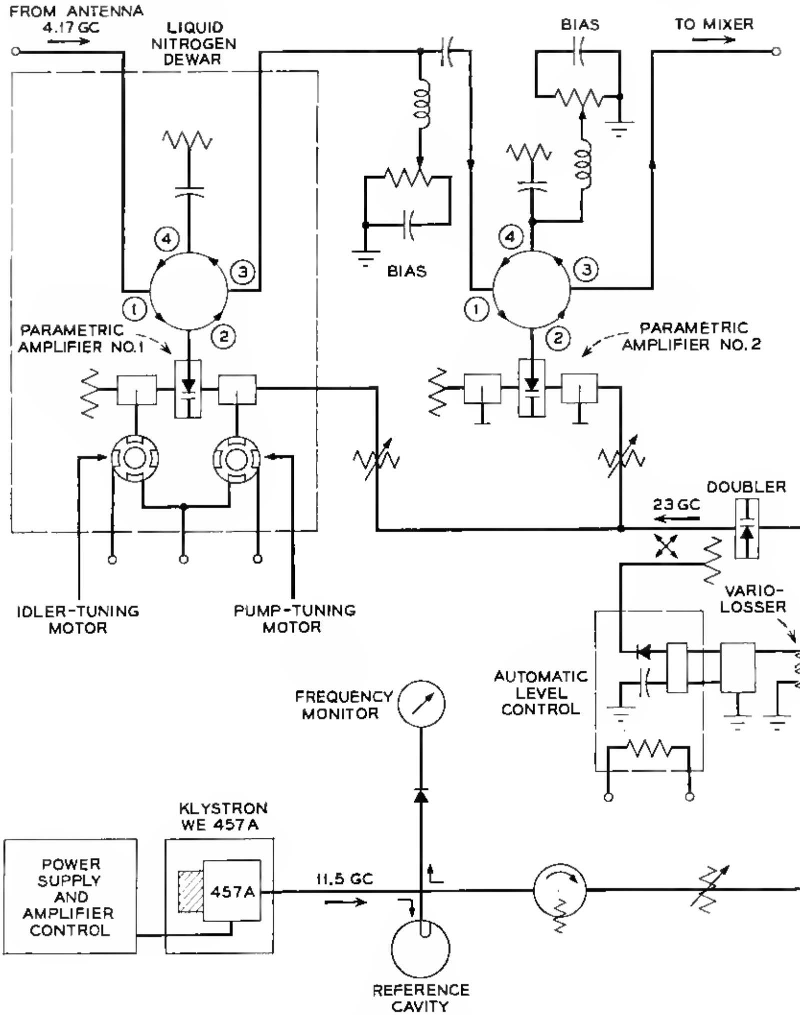

Fig. 1 — Block diagram of parametric receiver.

K-band termination for the external idler load, and two stepping motors for tuning the idler and pump circuits are all completely enclosed in a sealed copper can immersed in a liquid nitrogen dewar. This refrigerated amplifier is followed by a room temperature amplifier of the same design. Since the regenerative reflection mode of operation is used, there is no frequency conversion from input to output. The same 23-gc pump source supplies power to both amplifiers.

The gain stability of the parametric amplifier is largely dependent upon the stability of pump power level and frequency. Therefore, considerable effort has been spent to develop a pump source that would satisfy the most exacting requirements. The 23-gc source is derived from an X-band frequency-stabilized klystron of proven reliability (Western Electric 457A)[1] and a varactor frequency doubler.[2] An automatic level control is used to maintain a constant output power.

An efficient cryogenic system is required for operational simplicity and satisfactory amplifier performance. Such a system has been designed to maintain the amplifier at liquid nitrogen temperature. The dewar contains about 10 liters of liquid nitrogen and lasts more than ten days. This corresponds to an evaporation rate of 40 cc per hour or a heat inflow of 1.8 watts.

The two-stage amplifier provides a gain of 38 db at 4.17 gc with a minimum bandwidth of 60 mc. Over the entire band the effective system input noise temperature is less than 45°K. An input signal of -43 dbm produces 1-db gain compression when the small-signal gain is 38 db. Short-term gain fluctuations are less than 0.1 db and long-term gain variations are less than 0.3 db over periods of months. The amplifiers were installed in the ground station receivers at Andover and Holmdel and have been checked out to be satisfactory.

II. DESIGN CONSIDERATIONS

2.1 *Parametric Amplifier*

2.1.1 *Varactor Diode Considerations*

There are several factors which governed the choice of the varactor diode for the 4.17-gc refrigerated parametric amplifier. These include:

(a) A capacitive impedance of the same order as the circulator.[3]

(b) High dynamic quality factor[4] ($\tilde{Q}$) given by

$$\tilde{Q} = \frac{S_1}{2\omega R_S} = \frac{\text{Total reactance variation}}{4R_S}$$

where S_1 is the Fourier coefficient of the first-order term in the pumped variable elastance and R_S is the spreading resistance of the diode.

(c) Crystal suitability for operation at liquid nitrogen temperature.[5] The spreading resistance should decrease or at least remain constant down to liquid nitrogen temperature. To simplify amplifier design and adjustment, a small decrease in junction capacitance from room temperature to liquid nitrogen temperature is desirable.

(d) A self-resonant frequency of the diode higher than an idler frequency is preferred.

At the time this amplifier was designed no diode was available which would meet all these requirements. Since a gallium arsenide diode satisfied all conditions but the last, which was not essential, it was chosen for this application. It was originally developed by W. M. Sharpless[6] and was further developed by N. C. Vanderwal. The recent encapsulation of the sealed diode is shown in Fig. 2.

Typical data for the diode are tabulated in Table I.

The spreading resistance decreases about 10 per cent from room temperature to liquid nitrogen temperature, and the junction capacitance changes only 5 per cent. Representative impedance loci of the diode at 300°K and 77°K (measured at 5.85 gc) are plotted in Fig. 3. The normal bias voltage for operation at liquid nitrogen temperature is -1.1 volts.

2.1.2 *Amplifier Design Considerations*

The main objective of the amplifier design was to achieve the best possible noise performance with moderate bandwidth (i.e., 25-mc minimum, 50-mc desired) and thus satisfy the system requirement with the available diode described in the previous section. The amplifier was required to have stable and reliable performance.

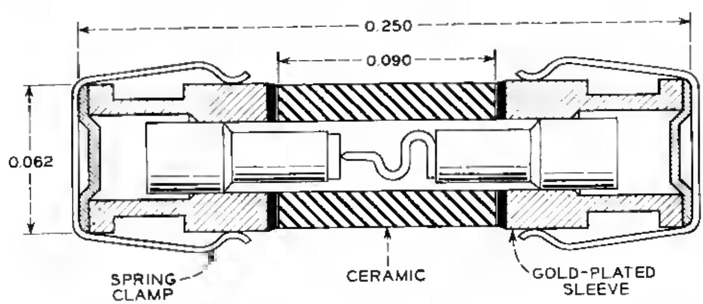

Fig. 2 — Encapsulation of sealed diode.

Table I

Static capacitance (C_0) at zero bias	0.37–0.46 pf (includes about 0.07 pf package capacitance)
Series inductance (L_s)	$\approx$1.2 nh
Self-resonant frequency (f_{res})	7.3–8.4 gc
Dynamic quality factor (Q)	9.0–14 at 4.17 gc
Reverse breakdown voltage (V_b)	5.0–6.0 volts (at 1 μa current)

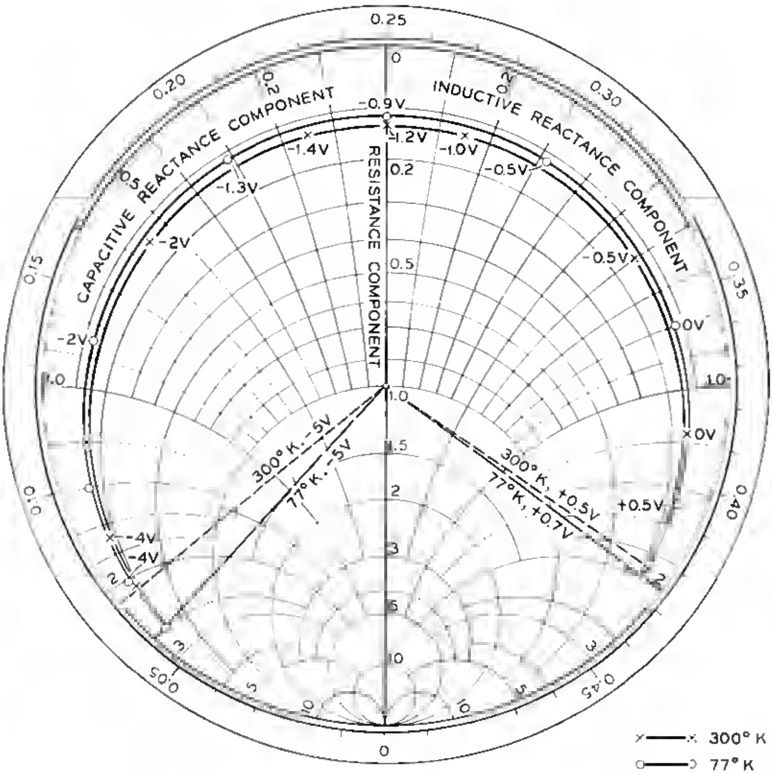

Fig. 3 — Impedance loci of input circuit at 300°K and 77°K (measured at 5.85 gc). Dynamic quality factor is 7.8 at 300°K and 9.3 at 77°K.

To achieve optimum performance, many factors, including the pump source, circuit elements and the cryogenic system, were carefully investigated. The detailed design considerations of the pump source and the cryogenic system are described in the following sections; however, selection of the pump frequency is discussed here since it primarily determines the circuit design of the amplifier.

The optimum ratio of idler frequency (f_2) to signal frequency (f_1) for best noise performance[3] is

$$\frac{f_2}{f_1} = \sqrt{1 + \frac{\tilde{Q}_1^2}{1 + \frac{R_L}{R_S}}} - 1 \tag{1}$$

where $\tilde{Q}_1$ is the dynamic quality factor of the input circuit and R_L/R_S is the external idler loading factor. Assuming the external idler loading

factor $R_L/R_S = 0.8$, which is discussed later, and using a diode whose dynamic quality factor at the signal frequency is 10, the optimum pump frequency is 31.6 gc. Unfortunately, a reflex klystron with the desired reliability was not available near this frequency. In addition, most klystrons which provide more than 100 mw of power at K-band need very high voltage supplies. Another factor was that none of these tubes provide satisfactory frequency stability without an elaborate scheme to compensate for any large environmental temperature variation and for mechanical vibration. However, a Western Electric 457A klystron (available from 10.7 to 11.7 gc) has high frequency stability with a simple closed vapor-phase cooling system.[1] Typically, the frequency variation is less than 2 mc from −20°F to +120°F ambient temperature. This klystron provides more than 500 mw power at 11.5 gc with about 500 volts cavity voltage. With a varactor frequency doubler,[2] this klystron can generate about 100 mw of power at 23 gc even after taking an additional 2-db loss for an automatic level control. The increase in noise temperature due to the utilization of a 23-gc pump source instead of a 31-gc pump source is calculated from the following equation;[3] the effective input noise temperature for a reflection type amplifier

$$T_e = \left(1 - \frac{1}{G_{11}}\right) \frac{1 + \left(\dfrac{f_1}{f_2}\right)^2 \dfrac{\tilde{Q}_1^2}{1 + \dfrac{R_L}{R_S}}}{\left(\dfrac{f_1}{f_2}\right) \dfrac{\tilde{Q}_1^2}{1 + \dfrac{R_L}{R_S}} - 1} \cdot T \qquad (2)$$

where G_{11} is a reflection power gain and T is the amplifier temperature. From (2), we obtain that the noise temperature degradation is only 1.5°K. Because of the reasons just described, a 23-gc pump was selected for this amplifier. This produces a center-band idler frequency of 18.83 gc. Fig. 4 shows curves of the effective input noise temperature of the amplifier at liquid nitrogen temperature for $f_2/f_1 = 4.52$. Curves are plotted as a function of external idler loading factor (R_L/R_S) for given values of input dynamic quality factor $\tilde{Q}_1$.

To achieve the noise performance shown in Fig. 4, the input circuit must be designed properly. The maximum normalized generator impedance (R_g/R_S) which provides 20 db of reflection gain for a given $\tilde{Q}_1$ and R_L/R_S is calculated[3] and plotted as a function of R_L/R_S in Fig. 5.

The first and second-stage amplifiers utilize the same design, a design

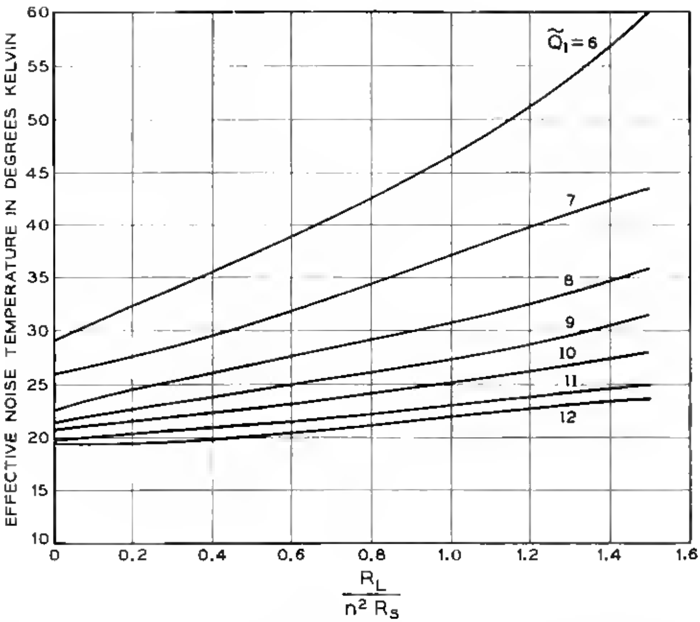

Fig. 4 — Effective input noise temperature of amplifier at liquid nitrogen temperature and room temperature as a function of external idler loading factor (R_L/R_S) for various $\tilde{Q}$.

which is similar to a 6-gc amplifier previously reported.[7] Fig. 6 shows a photograph of the amplifier mount with a four-port circulator. The input circuit is a 50-ohm coaxial line and the pump and idler circuits are in RG 66/U waveguide which houses a gallium arsenide point-contact diode at the end of the input center conductor. Since the diode sustains at least three frequencies (i.e., signal, idler and pump), filters must be arranged properly to eliminate unwanted interference among the three circuits. These filters are located as close as possible to the diode to minimize energy storage at the idler frequency. The input circuit contains two coaxial chokes for the pump and idler frequencies and a coaxial capacitor which is used to adjust the input coupling to the predetermined value of R_g/R_S and to tune the circuit at a desired bias voltage. These chokes and the rest of the mount are brazed into one piece for mechanical rigidity and electrical stability. The coaxial capacitor is movable along the center conductor to tune the circuit at a desired bias voltage. The input coupling is adjusted by using a different diameter coaxial capacitor.

One of the major design objectives was to increase the bandwidth

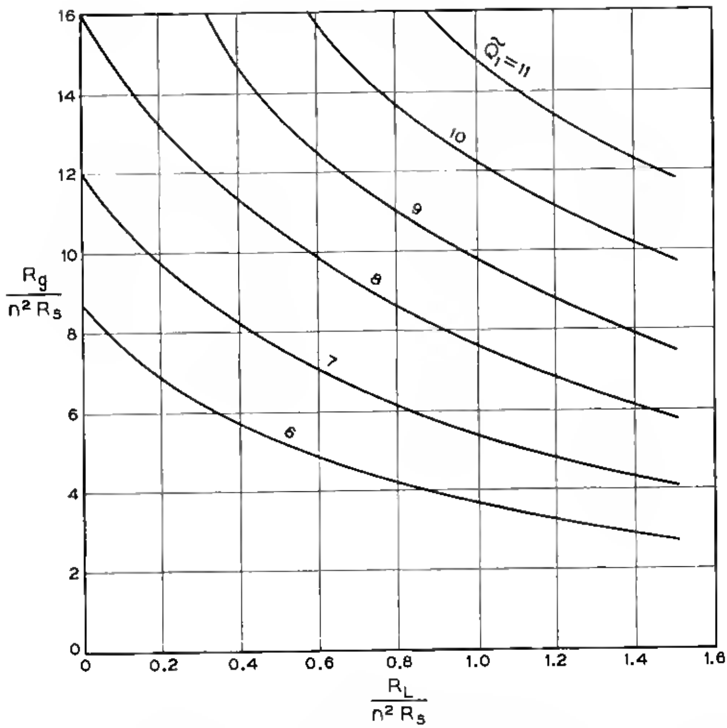

Fig. 5 — Normalized generator impedance R_g/R_S required for 20-db regenerative gain as a function of external idler loading factor R_L/R_S for given values of input circuit dynamic quality-factor $\tilde{Q}$.

without sacrificing noise performance. Since the self-resonant frequency of the diode is approximately 8 gc, it is unavoidable that an idler frequency much higher than the self-resonant frequency must be used. This resulted in an idler circuit of very high Q and complicated impedance. It was found that the 3-db bandwidth with 20-db center-band gain was less than 20 mc when there was no external idler loading or compensation circuit. Since the input circuit was broad enough, a compensation circuit was inserted in the idler circuit to improve the bandwidth. When the idler circuit Q is sufficiently high, the bandwidth can be improved by external idler loading. The optimum idler loading factor $(R_L/R_S)_{\text{opt}}$ for the case where the idler frequency is above the self-resonant frequency f_{res} of the diode is given in terms of $\tilde{Q}_1$, f_1/f_2 and f_{res}/f_1 as follows[8]

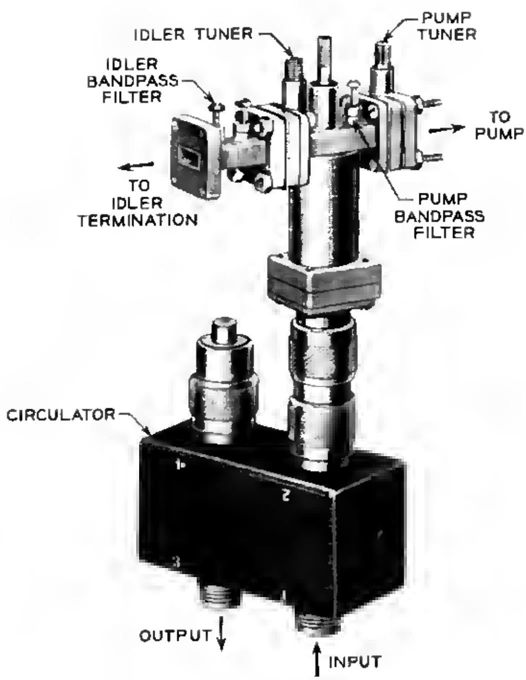

Fig. 6 — Photograph of 4.17-gc parametric amplifier and refrigerated circulator.

$$\left(\frac{R_L}{R_S}\right)_{\text{opt}} \approx \tilde{Q}_1^2\left(\frac{f_1}{f_2}\right)\left[\frac{1}{1+\sqrt{1+\tilde{Q}_1^2\left(\frac{f_{\text{res}}}{f_1}\right)^2\left(\frac{f_1}{f_2}\right)}}\right]-1\,. \qquad (3)$$

For the case where $\tilde{Q}_1 = 10, f_1/f_2 = 0.22$ and $f_{\text{res}}/f_1 = 1.9$, this equation shows that $(R_L/R_S)_{\text{opt}} = 1.15$. According to the curves in Fig. 4, the noise degradation caused by this external load is about 5°K; a suitable compromise between optimum gain-bandwidth and optimum noise performance is $R_L/R_S = 0.8$. This reduces the noise degradation to about 3°K. As a compensation circuit, a two-cavity bandpass filter was added adjacent to the inductive iris which tunes the idler circuit at the prescribed diode bias voltage. This iris also determines the coupling between the diode and the external idler load. The electrical separation between the iris and the filter and the filter impedance characteristic were properly adjusted for the maximum bandwidth. A Teflon tuner

was located in the idler resonant cavity to compensate for the approximate 20 per cent change in circuit impedance from room temperature to liquid nitrogen temperature due to the reduction in junction capacitance and cavity volume.

The pump filter was built in the mount as close as possible to the diode to minimize idler frequency energy storage in the idler cavity. A Teflon tuner, an inductive iris adjacent to the amplifier, and a screw in the pump filter are used for critical matched tuning and compensation from room temperature to liquid nitrogen temperature operation.

The bias voltage of the diode was applied through the third or fourth port of the four-port circulator. Any loss and instability usually caused by the bias supply circuit in the diode mount were completely eliminated.

A circulator operated at liquid nitrogen temperature (Raytheon CCL-12) was specially designed for the refrigerated first-stage amplifier. It was designed to have a maximum insertion loss from port 1 to port 2 of 0.2 db and isolation of at least 30 db. The room temperature circulator for the second-stage amplifier is the broadband Melabs X-626. Its characteristics at room temperature are similar to those of the CCL-12 at liquid nitrogen temperature.

The main design features of the amplifier are given in Table II.

2.2 *Pump Source*

The design of parametric amplifiers usually calls for high stability in both the frequency and amplitude of the pump source. The troubles often ascribed to parametric amplifiers, such as frequent failure and high cost, can largely be attributed to unsatisfactory pump sources. Therefore, considerable effort was devoted to obtain the simplest pump source that would satisfy the exacting requirements.

For frequency stabilization and compactness an all solid-state source is most attractive. This would consist of a transistorized crystal oscillator at a relatively low frequency with power amplification and subse-

Table II

Input and output frequency	4.17 gc ± 30 mc
Pump frequency	≈23 gc
Dynamic quality factor $\tilde{Q}$ (including the circuit loss)	10 at 4.17 gc, 2.3 at 18.83 gc
Normalized generator impedance (R_g/R_S)	13.0
Normalized idler impedance (R_L/R_S)	0.8
Gain	20 db
Estimated noise temperature from (2) (amplifier alone)	94°K at 300°K 25°K at 77°K

quent multiplication by varactor diodes. While technically possible, such a device was not available in time for this project. Therefore, the WE 457A klystron was used as an 11.5-gc source to drive the varactor frequency doubler,[2] which produced the required 23-gc pump power.

For the automatic level control (ALC) the classical feedback approach has been used. A block diagram of the ALC arrangement is shown in Fig. 7. The output of the klystron is fed into the doubler through a Faraday rotational variolosser.[9] A small fraction of the 23-gc output is detected by a 1N26 crystal in the sampling port of a cross guide coupler. This output is compared with a reference voltage, amplified by a transistorized differential amplifier, and is fed to the variolosser. In this way the difference between the sampling voltage and the reference voltage is kept close to a preset constant value, and hence the 23-gc power output level is stabilized to better than 0.5 per cent over long time periods. Since the sensing diode characteristic is influenced by a large temperature change, this diode and the first stage of the differential amplifier are mounted in a small oven.

The second design, shown in Fig. 8, omitted the variolosser and operated directly on the doubler bias to control the output power. Although the performance was generally satisfactory, it demonstrated the need for an additional control factor. For feedback stability reasons, it is necessary to place a limit on the bias. However, this limit varies with input power to the doubler diode; hence, some additional circuitry is added to automatically set the maximum bias consistent with the input power.

The varactor frequency doubler from 11.5 gc to 23 gc used for this pump source can generate more than 200 mw of power at 23 gc with as low as 3.7-db conversion loss. The instantaneous 3-db bandwidth is about 300 mc, and no spurious oscillation is observable except at a bias

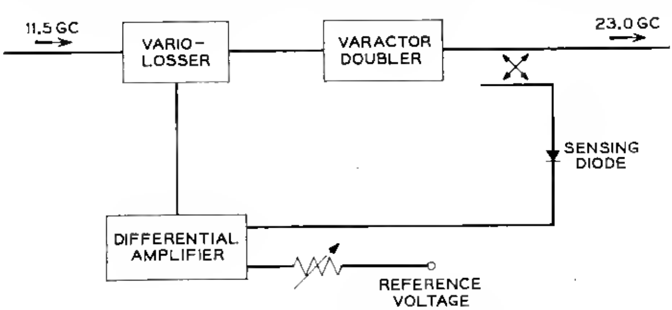

Fig. 7 — Block diagram of ALC arrangement. Power level is controlled by variolosser.

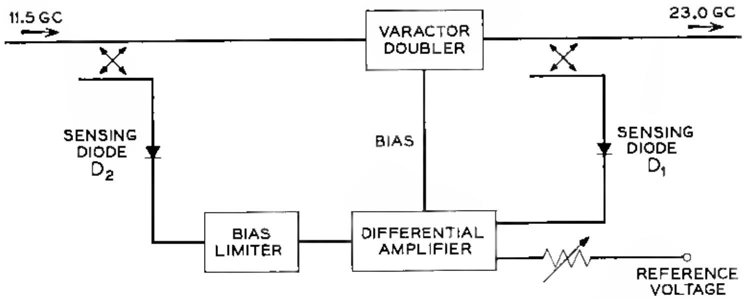

Fig. 8 — Block diagram of varactor diode bias-controlled ALC arrangement.

voltage which is much higher than the optimum. The varactor diode used is the epitaxial silicon mesa diode developed at Bell Telephone Laboratories. The diode has a cutoff frequency as high as 300 gc at −2.5 volts bias and a 25 volts average reverse breakdown voltage.

2.3 *Cryogenic System*

It was necessary for simple maintenance and satisfactory amplifier performance to design an efficient cryogenic system. Noise considerations dictate that not only the diode but also the total structure of the first-stage amplifier, including the circulator and the idler load, should be refrigerated. Immersing the whole amplifier in liquid nitrogen is a convenient way of refrigerating. However, it is very difficult to seal all parts of such a complex geometry in order to avoid liquid nitrogen leakage, which produces erratic electrical performance. Therefore, the whole unit is enclosed in a tight cylindrical copper vessel which is then immersed in liquid nitrogen. The walls of this vessel will assume a temperature of 77°K and cool the whole interior by conduction and radiation.

In order to achieve a long operating time with each filling of tbe dewar, the heat input must be minimized through the proper use of materials of low thermal conductivity. The design must make full use of the cryogenic value of the refrigerant. One liter of liquid nitrogen can absorb 38,600 cal. as heat of vaporization, and in addition the nitrogen gas which is produced can absorb 39,000 cal. when brought from 77°K to 273°K. If an arrangement can be made so that the nitrogen gas leaves the dewar with a temperature equal to that of ice, for instance, then the cryogenic value of one liter of liquid nitrogen is 77,600 cal. Furthermore, if the nitrogen gas escapes at room temperature there will be no condensation or freeze-out of moisture at the lid of the dewar, where many

electrical connections are located. A long operating time between refills can be obtained by immersing the amplifier deeply into the coolant; on the other hand, the input transmission line to the amplifier must be short to keep its loss and the corresponding noise contribution down. This imposes some restrictions on the cryogenic design. Fig. 9 shows a drawing of the cryostat. A commercial Linde Dewar featuring "Super Insulation" was chosen. It has a necktube of 5.5 inches diameter and holds 13.5 liters of liquid nitrogen. Part of this volume is taken up by the amplifier chamber, so that about 10 liters of liquid nitrogen are available for refrigeration. After immersion of the copper vessel the necktube is closed off by a lid consisting of a grooved Teflon plug, to the bottom of

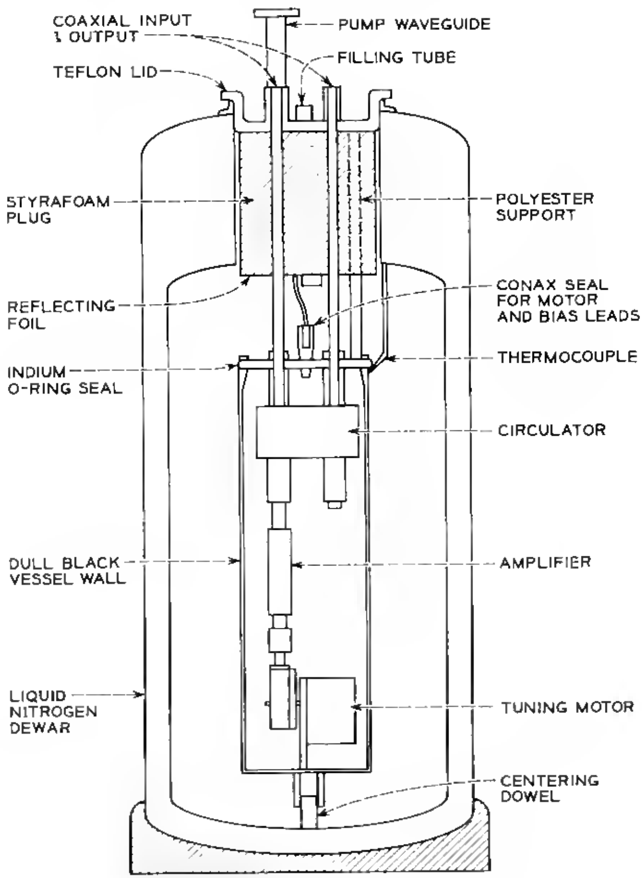

Fig. 9 — Cryostat for parametric amplifier.

which is glued a styrofoam cylinder 4 inches deep and $\frac{1}{8}$ inch smaller in diameter than the necktube. This arrangement forces the nitrogen gas to rise along the wall of the necktube and thereby cools it. The pump waveguide, two coaxial lines, a Teflon filling tube, and two polyester support rods (which add mechanical strength to the structure) pass through this lid down to the top of the amplifier chamber. The 11-inch input and output coaxial lines are made of 5-mil wall stainless steel tubes with 0.5-mil copper clad interior. Thin-wall stainless steel waveguide with silver plated interior is used for the pump waveguide. These transmission lines are vacuum sealed at the neck of the dewar (where the temperature is higher than the dew point) to prevent moisture condensation. The top of the copper chamber is sealed vacuum tight by an indium O-ring and the lower end extends almost to the bottom of the dewar, where it is held centered by a dowel pin. After all the parts are assembled, the copper chamber is tested on a helium leak tester for perfect sealing. The inside pressure of the chamber is left at atmospheric pressure to improve the speed of cooling.

With one filling of the dewar the amplifier was held for 10.5 days at liquid nitrogen temperature. This corresponds to an evaporation rate of 40 cc per hour or a heat inflow of 1.8 watts. Vertical temperature profiles which have been measured in the dewar reveal that the temperature of the gas above the liquid level stays within 2° of 77°K. This explains the constancy of the amplifier temperature over such a long time. The dewar can be refilled with liquid nitrogen without interrupting the performance of the parametric receiver.

For remote tuning of the idler and pump circuits, two tuning motors are mounted on the bottom of the copper vessel. Motors which are designed to be run at liquid nitrogen temperature must have a high starting torque, slow speed, and bearings which will not seize when the materials contract upon cooling. A stepping motor with 100 steps per revolution has been found to be the most reliable device to satisfy these requirements. The motors are operated by a transistorized multivibrator.

2.4 *Package*

One of the advantages of a parametric amplifier over a maser can be its compactness; however, its size is largely dependent upon the package design. Since the amplifier is highly susceptible to impedance variations and pump fluctuations, the package has to be designed not only for compactness but also to minimize any electrical malfunctions due to mechanical vibrations. Easier maintenance is also an important consideration for the package design.

Three different types of the package were constructed. Each of the first two amplifiers was packaged in a large 28 inch × 26 inch × 72 inch cabinet which can directly replace the maser cabinet and match mechanically to the horn antenna. This package was designed for operational convenience, reliability, simple maintenance and appearance. The front and back views of the amplifier are shown in Figs. 10 and 11. The dewar containing the refrigerated amplifier is in a frame at the top of the rack, with the input waveguide above the cabinet at a total height of 78 inches. The cabinet has four leveling jacks to enable an exact match to the antenna. The room temperature amplifier is mounted on

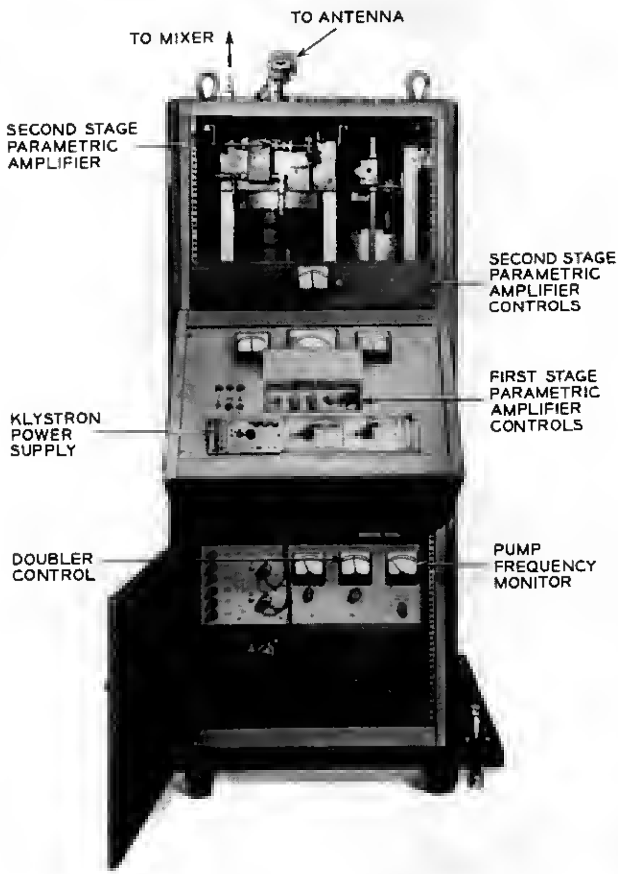

Fig. 10 — Front view of large amplifier package.

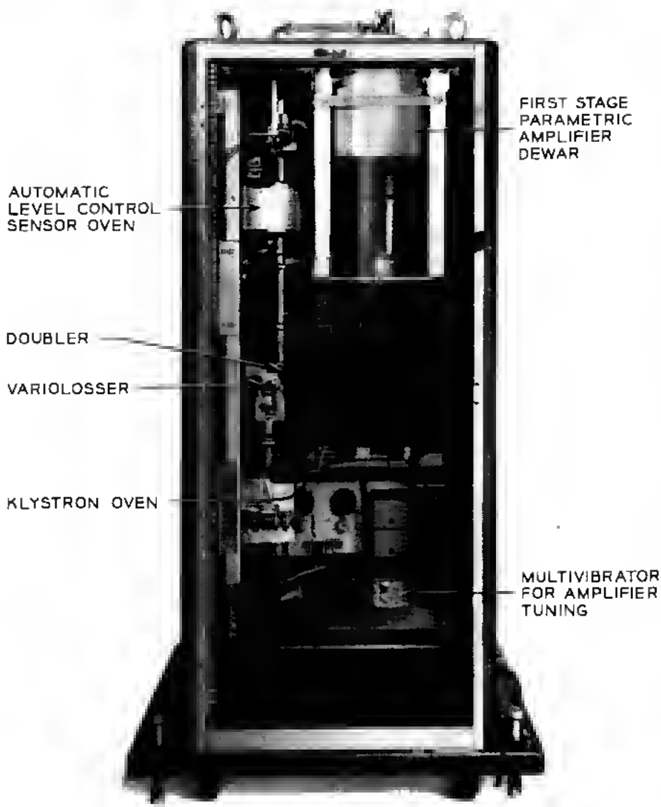

Fig. 11 — Back view of large amplifier package.

the dewar frame to minimize the interconnecting transmission line length and can be seen from the front of the rack with the top panel removed. The bias and pump power controls for the room temperature amplifier are located on the top control panel, and the controls for the liquid nitrogen temperature amplifier and the ALC are located in the recessed middle control panel. This section is usually covered and protected from accidental handling. The entire pump supply is mounted on a flat aluminum chassis which is fastened on the left side frame structure. The length of pump waveguides and the number of flange connections from the pump power sampling point to the amplifiers are minimized to maintain constant pump power levels against mechanical vibrations. The pump power level can be controlled by the motor-

driven waveguide attenuators from the front panel. One can see that the cabinet is only partially occupied.

To utilize full advantage of the parametric amplifier, a compact package was designed. This package consists of two cabinets: a control cabinet (17 inches × 18 inches × 10 inches) and an amplifier cabinet (14 inches × 14 inches × 32 inches), both shown in Fig. 12. The separation thus allowed the amplifier to be installed directly at the antenna output and the controls to be located at a convenient operating location. In this compact model, the doubler bias-controlled ALC is installed to ease the package design. Fig. 13 shows the amplifier and pump arrangement.

III. PERFORMANCE

Five parametric receivers were built: two were housed in large cabinets, two in compact cabinets, and one in a special cabinet for a sky

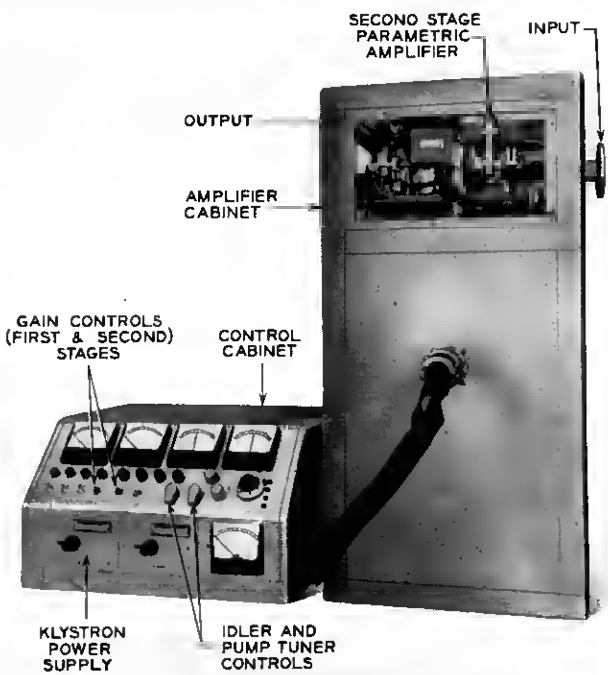

Fig. 12 — Photograph of compact package.

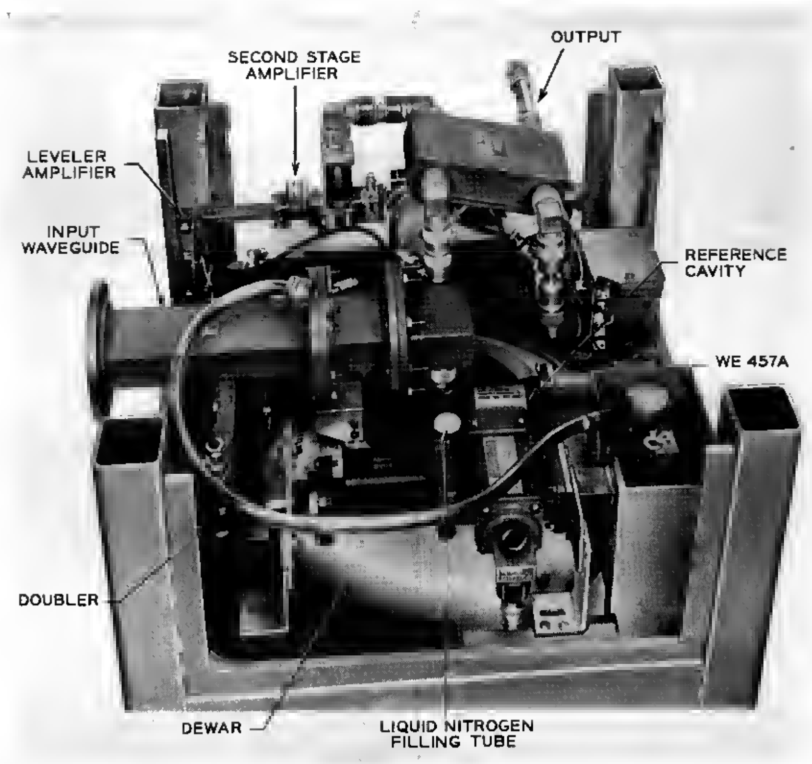

Fig. 13 — Photograph of amplifier and pump arrangement of compact package.

temperature measurement. The average values for the performance of these amplifiers are listed in Table III.

By December 1, 1962, amplifier no. 1 had been operated continuously for 6000 hours (since March 20, 1962) without any failure or degradation.

A representative gain-frequency band characteristic is shown in Fig. 14. Fig. 15 shows the recorded data on amplifier stability over a two-day period. The bottom f_p curve shows the pump frequency deviation from 23 gc. One inch on the original recording paper corresponds to about 200 kc deviation. The second curve from the bottom (gain) shows the gain of the refrigerated amplifier. One inch corresponds to 1-db change in gain. The P_{pump} curve indicates the pump power level. The scale is 0.25 db per 0.5 inch. Since the signal generator and the test receiver used for the stability tests did not themselves have absolute gain stability, both input and output signal level were detected by crystal detectors and were recorded simultaneously. The second (P_{in})

TABLE III

Gain	38 db (first stage 20 db, second stage 18 db)
Bandwidth	60 mc to 3-db points
Noise temperature	<45°K
First stage	<43°K
Contribution from second stage + mixer	<2°K
Gain stability	
Short-term	<0.1 db
Long-term	<0.3 db
Gain compression	1 db down at −5 dbm output
23-gc pump power required	≈20 mw for each stage
Pump stability	
Frequency	Short-term <100 kc Long-term <2 mc
Power	<0.02 db
Dewar — nitrogen service	Once a week (nitrogen lasts about 10 days)

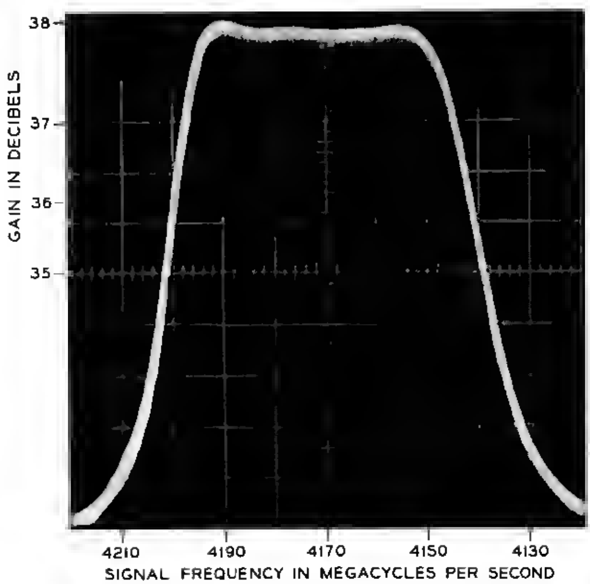

Fig. 14 — Gain-frequency band characteristic of parametric amplifier no. 2.

and third (P_{out} − 21 db) curves show these outputs. The controls were adjusted so that the separation between the two curves was 1 db when the gain of the amplifier was 20 db; the gain fluctuations were then deduced from the separation of these curves. The speed of the recorder was two inches per hour.

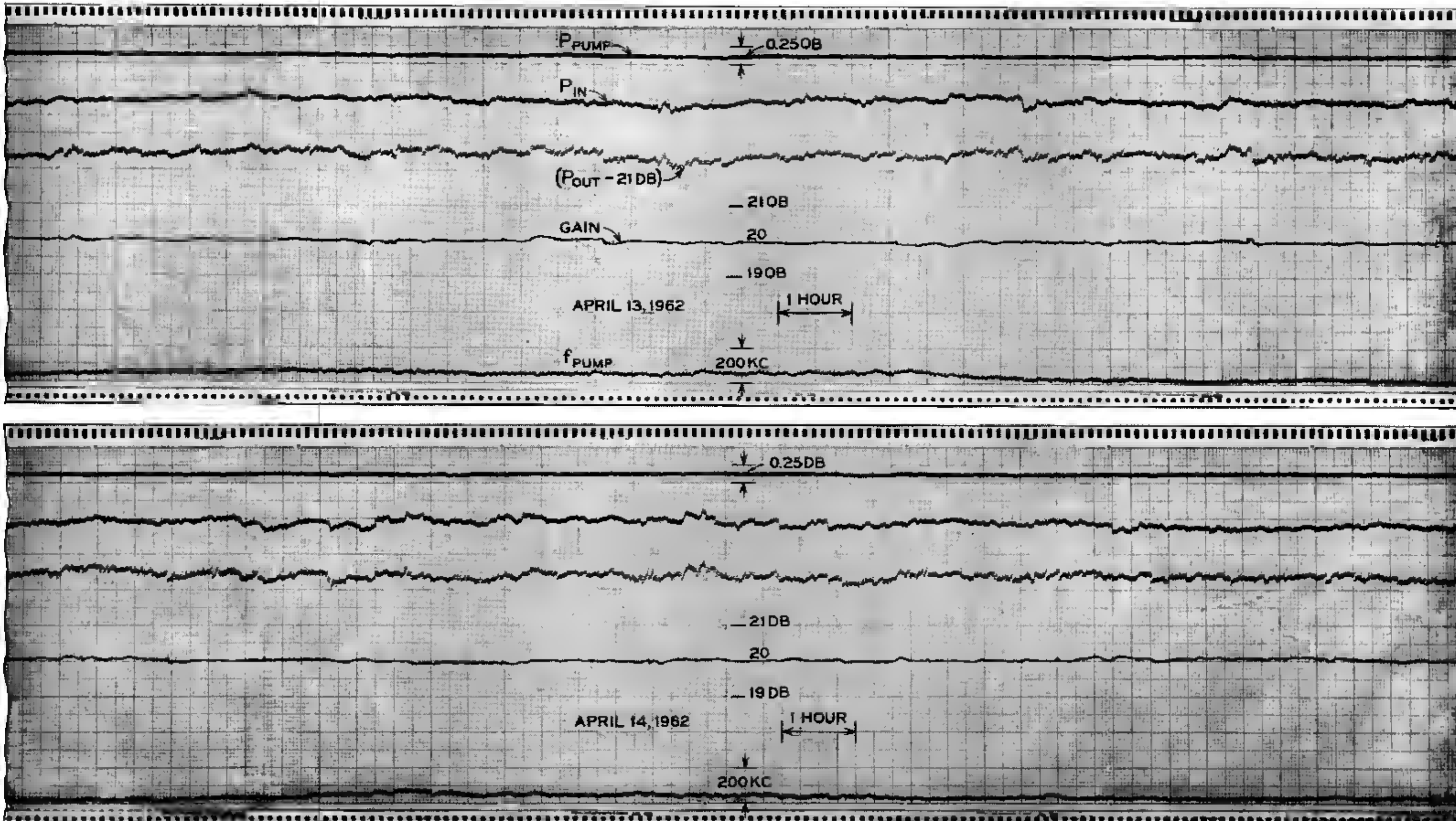

Fig. 15 — Recorded graph of amplifier stability. Pump line shows the pump power level; P_{in}, signal input; $P_{\text{out}} - 21$ db, 21 db below amplifier output; f_{pump} the pump frequency deviation from 23 gc.

The amplifiers were installed in the satellite ground stations both at Andover, Maine, and Holmdel, New Jersey, and were checked out as functioning satisfactorily. The complete system noise temperature of the receiver at the Andover station with the parametric amplifier was about 80°K when the antenna was directed at the zenith. This noise temperature includes about 28°K of noise from the sky, the radome, the antenna and the diplexer, and some noise from the 2.5-foot long waveguide which connects the amplifier to the diplexer.

IV. CONCLUSION

The noise temperature of the receiver with the parametric preamplifier is 2.5 times that with the maser. However, the parametric amplifier is much cheaper to operate. The results of laboratory and field tests demonstrate that the parametric receiver meets the stringent requirements of a satellite ground station receiver. The stability performance of the amplifier also proves that a carefully engineered parametric amplifier is as stable as conventional microwave amplifiers.

The amplifier and its associated devices have been designed for high sensitivity, stability, and reliability. To assure this performance, the bandwidth was sacrificed and in many places a conservative design has been adopted. With an improved diode—in particular, one in a more suitable package—and a completely transistorized pump source, the amplifier can be considerably simplified and made very compact without any degradation in its performance and with an improved bandwidth.

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